NUMERICAL SIMULATION OF INTEGRATED SURFACE WATER/GROUNDWATER FLOW AND SOLUTE TRANSPORT IN THE SOUTHERN EVERGLADES, FLORIDA

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Abstract: A numerical model was developed for the southern Everglades in Florida to represent the response of flow and salinity patterns to hydrologic events and to evaluate the complex exchange of water and dissolved salt between the wetland, the estuary, and the underlying Biscayne aquifer. The effort included the development of a coupled surface water and groundwater simulation code as well as application of the code to the southern Everglades hydrologic system. A 22-month simulation was performed with the integrated code to represent the period from August 1996 to June 1998. The integrated model was calibrated by matching surface water stages, coastal creek flows and salinities, and groundwater heads and salinities. Results from the model suggest that exchange of fluid and salt between surface water and groundwater is spatially and temporally variable. Results also suggest an alternating pattern of downward and upward leakage from north to south. Averages of the downward simulated leakage rates and the upward simulated leakage rates are –20 and 30 centimeters per year, respectively. These complex leakage patterns contribute to the overall salinity distribution in the surface-water regime and aquifer system and are required for accurate simulation of flow and transport in the study area. Model results indicate that surface water and groundwater interactions may be an important component of the water budget for the Taylor Slough area, although, rainfall and evapotranspiration are probably the dominant components.

INTRODUCTION

The hydrology of southern Florida is unique due to the high degree of connection between surface water and groundwater. The connection occurs as upward or downward leakage, defined as the flux of water between a surface water body and an underlying aquifer. In an analysis of surface water and groundwater hydrographs within the southern part of the Everglades, Merritt (1996) indicates that surface water and groundwater remain well connected at daily and monthly time scales despite peat and marl units that restrict vertical leakage. In the Taylor Slough area (Figure 1) of the southern Everglades, Harvey et al. (2000a) reported groundwater leakage upward into the slough at rates of up to 3 cm/day, nearly an order of magnitude higher than rainfall and evapotranspiration, which are normally considered the dominant processes. In southern Florida, most studies of surface water and groundwater interactions have focused on areas near canals, but few studies have investigated hydrologic groundwater-surface water wetland interactions in the Everglades.

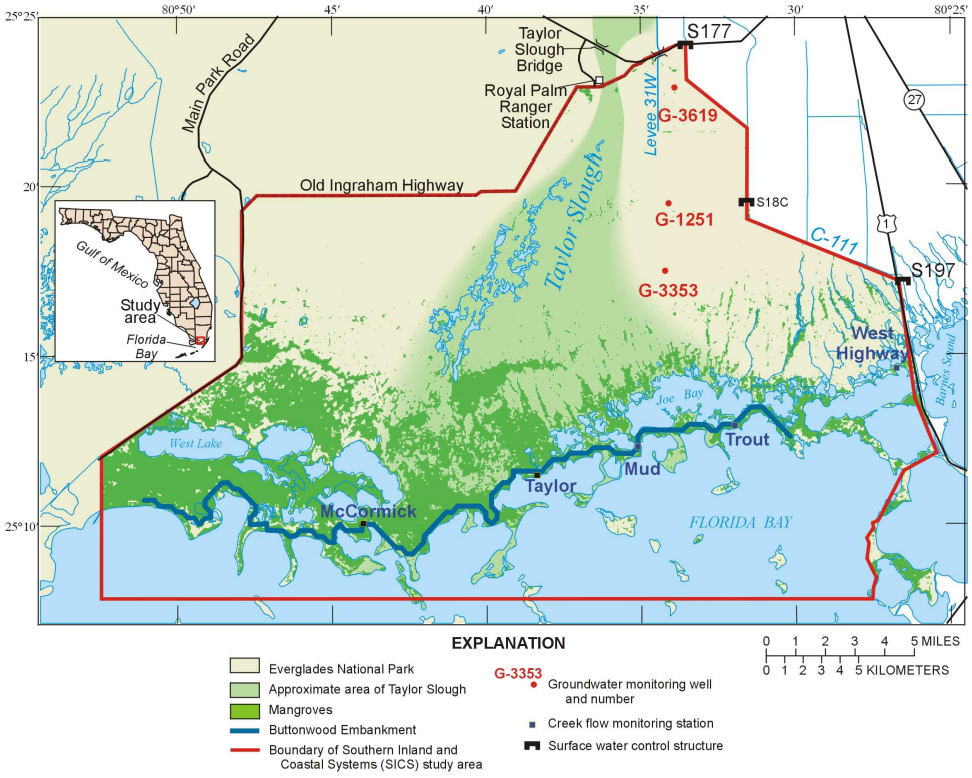

Figure 1. Map showing the Taylor Slough study area, monitoring sites, and physiographic features.

The Taylor Slough area in Everglades National Park has been the focus of governmental restoration efforts because the area is ecologically diverse, hosting a variety of animal and plant species. Some threatened or endangered species include: wading birds, crocodiles, and alligators. The slough is hydrologically important because it is a major source of freshwater for the northern part of the Florida Bay estuary. The slough, however, does not flow unimpeded into the estuary. The Buttonwood Embankment, a narrow topographic high, hydraulically separates Taylor Slough and Florida Bay (Figure 1). Field reconnaissance indicates that creeks discharge nearly all of the fresh surface water into Florida Bay. For most of the year, coastal creeks funnel fresh or brackish water into Florida Bay; however, southerly winds commonly push brackish water from Florida Bay northward into Taylor Slough. The interface between Taylor Slough and Florida Bay acts differently than most coastal wetlands because eastern Florida Bay does not have a prominent tidal signature. Only minor tidal fluctuations are exhibited at monitoring sites because mud banks and scattered mangrove islands dampen the tidal exchange with the Gulf of Mexico.

Groundwater seems to have a measurable effect on surface water salinity within Taylor Slough. A fluid conductivity probe placed on the rock bottom of Taylor River (located approximately 5 km north of the Florida Bay coastline) recorded pulses of saline water discharging into the creek during periods of relatively low stage. Another fluid conductivity probe at the same location, but higher in the surface water column, did not exhibit similar increases in salinity. Based on an analysis of the fluid conductivity data, the pulses of saline water recorded at the bottom of Taylor River do not appear to be caused by density stratification or inland surface water flow from

Florida Bay. Instead, these pulses appear to be caused by upward discharge of saline groundwater into the creek. Monitoring wells were recently installed at the Taylor Creek upstream station to further verify upward saline groundwater leakage. Preliminary data from the monitoring wells show significant salinity variations between surface water and shallow groundwater. The occurrence of saline groundwater beneath the southern part of Taylor Slough was confirmed on the basis of an airborne geophysical survey (Figure 2). This survey shows that the shallow subsurface interface between fresh groundwater and saline groundwater extends as much as 10 to 15 km inland from the Florida Bay coastline.

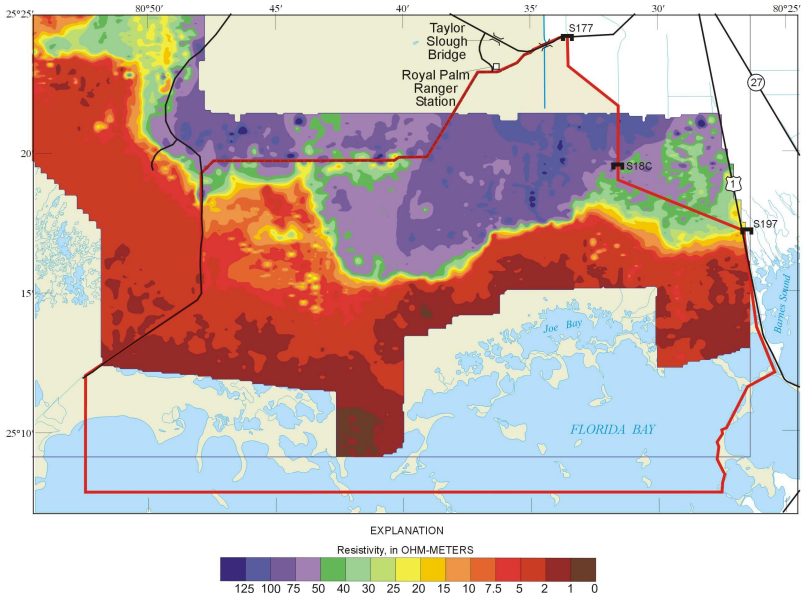

Figure 2. Map showing results from airborne geophysical survey (modified from Fitterman and Deszcz-Pan, 1998). Color shading represents formation resistivities 5 meters below land surface.

In an effort to better understand wetland hydrodynamics and salinity patterns in South Florida, the U.S. Geological Survey's Place-Based Studies program and the National Park Service's Critical Ecosystem Studies Initiative funded the development of the Southern Inland and Coastal Systems (SICS) model. The SICS model was originally designed to represent overland sheetflow in Taylor Slough and was developed with transport capabilities to simulate changes in surface water salinity. The plan for the original SICS surface water model was to use a simplified representation of groundwater leakage and then include a more sophisticated approach later. The more sophisticated approach, which was recently implemented, includes the development of a variable-density groundwater flow and transport model for the SICS area. A computer program also was developed that linked the hydrodynamic surface water model with the variable-density groundwater flow model. The purpose of this paper is to provide a description of the integrated model and present estimates of surface water and groundwater leakage for the SICS area.

MODEL CODE DESCRIPTIONS

SWIFT2D: Overland surface water flow and transport of dissolved salt can be simulated in two dimensions using the SWIFT2D (Surface Water Integrated Flow and Transport in 2 Dimensions) code (Leenderste, 1987). SWIFT2D is a fully dynamic circulation model that uses the finite-difference method to solve the momentum and conservation of mass equations. The SWIFT2D code was originally designed to simulate flow and transport in vertically well-mixed estuaries, coastal embayments, lakes, rivers, and inland waterways. The code was modified for this study to include such processes as rainfall, evapotranspiration, and flow resistance of marsh vegetation.

SEAWAT: Groundwater flow and transport of dissolved salt is simulated using the SEAWAT code (Guo and Langevin, 2002). The SEAWAT code was developed by combining MODFLOW (McDonald and Harbaugh, 1988) and MT3DMS (Zheng and Wang, 1998) to solve the variable-density groundwater flow equation formulated in terms of equivalent freshwater head, rather than pressure. The finite-difference method is used to solve the flow equation. A variety of techniques, including the finite-difference method, method of characteristics, and third-order total-variation-diminishing method, are available for solving the transport equation.

FTLOADDS: The SWIFT2D and SEAWAT codes were combined into a single program, referred to as FTLOADDS (Flow and Transport in a Linked Overland Aquifer Density Dependent System). In the FTLOADDS program, SWIFT2D and SEAWAT are subroutines called by the main program. FTLOADDS was designed to allow different timesteps between SWIFT2D and SEAWAT, because simulation of dynamic surface water flow often requires much shorter timesteps than is required for groundwater flow. To simulate transient groundwater flow, time is divided into stress periods, or periods of time when hydrologic stresses on the system remain constant. A single groundwater stress period may contain many surface water timesteps. For example, the groundwater model may have daily stress periods, but the surface water model may require timesteps that are as short as 15 minutes. In this case, there would be 96 timesteps per stress period.

The main linkage between SWIFT2D and SEAWAT is through a leakage quantity passed between the two models. First, SWIFT2D steps through the current stress period and then SEAWAT steps through the same stress period. In SWIFT2D, leakage is calculated using a variable-density form of Darcy's law, the current surface water stage, the groundwater head from the end of the previous stress period, and a leakage coefficient. SEAWAT then evenly applies the average leakage rate over the entire stress period. The transfer of salt mass between surface water and groundwater is treated in a similar manner. Upward leakage to the surface water is assumed to have the concentration of the underlying groundwater cell from the end of the previous stress period. Downward leakage is assumed to have the concentration of the surface water. At the end of the stress period, the cumulative salt flux is divided by the leakage rate to calculate the average concentration of the leakage. This average concentration and average leakage rate is then applied in the following stress period to the groundwater model. Using this approach, salt mass and fluid mass are conserved within the system.

Several other enhancements were programmed to respond when a surface water cell becomes dry. In this case, recharge and evapotranspiration are applied to the cells in the uppermost layer

in the groundwater model. The model code also includes the capability for upward leakage to rewet a surface water cell, which can be important to adequately represent isolated depressions in the land surface.

MODEL DESIGN

Spatial and Temporal Discretization: The surface water model was designed by discretizing the Taylor Slough area into a grid consisting of 148 columns and 98 rows (Figure 3). Each cell within the finite-difference grid is square with 304.8-m per side. The model grid encompasses most of Taylor Slough with the exception of the slough area north of Old Ingraham Highway. The groundwater model uses a three-dimensional finite-difference grid with the same extent and cell area as the surface water model. The three dimensional grid has 10 layers (each 3.2-m thick) and extends from land surface to a depth of 32 m.

The integrated model simulates flow and transport for a 22-month period from August 1996 to June 1998. There are a total of 679 one-day groundwater stress periods and 130,368 7.5-minute surface water timesteps. The model also includes a 15-day "warm-up period" in which only the surface water model runs.

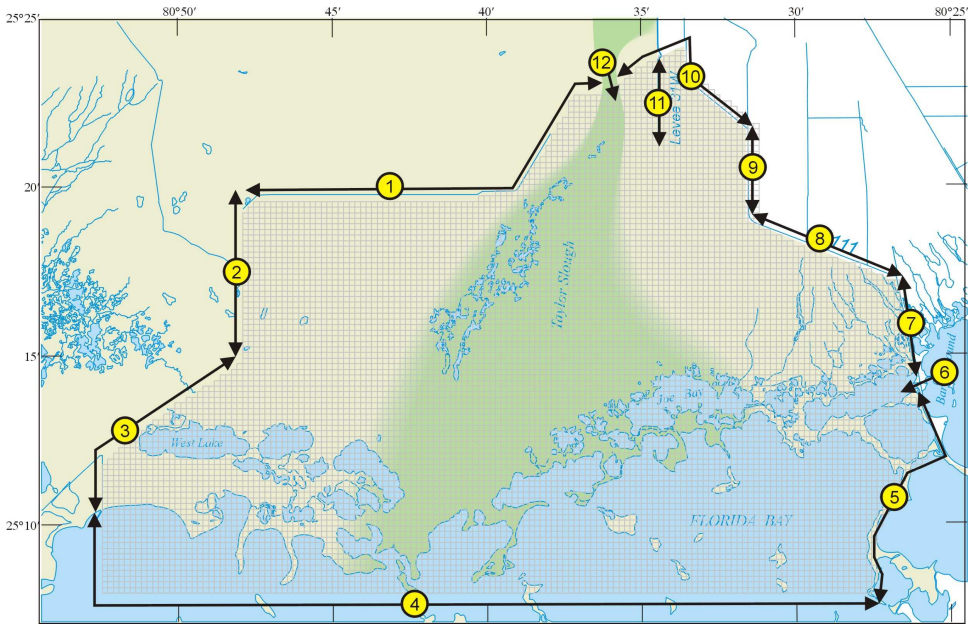

Figure 3. Map showing finite-difference model grid and locations of boundary conditions specified for the SWIFT2D and SEAWAT. Descriptions for each numbered boundary condition are shown in Table 1.

Boundary Conditions: Boundary conditions for the SWIFT2D surface water model were specified for the model perimeter based on the presence of roads, canals, culverts, islands, and an arbitrary offshore boundary (Figure 3). The type of boundary used for each segment in Figure 3 is listed in Table 1.

Table 1. Description of boundary conditions for surface water model. Locations for the boundary conditions are shown in Figure 3. [SD, specified discharge boundary; NF, no-flow boundary; SH, specified head boundary]

Identifying Number	*Description*	*Boundary Type*
1	Old Ingraham Highway (north)	SD
2	Old Ingraham Highway (west)	SH
3	Old Ingraham Highway (southwest)	NF
4	Florida Bay	SH
5	Florida Bay islands	NF
6	US-1 culverts	SH
7	C-111 tidal canal	NF
8	C-111 (S18C-S197)	SD
9	C-111 (north of S18C)	SH
10	C-111/Park Road	NF
11	L-31W	SD
12	Taylor Slough inflow	SD

For each layer of the SEAWAT groundwater model, a general-head boundary was applied to each cell on the model perimeter. The head values used for the boundaries were interpolated from nearby surface water and groundwater monitoring sites for each day of the simulation. Salinity values assigned to the general-head boundaries were estimated from the airborne geophysical data (Figure 2).

Model Input Parameters: A wide range of atmospheric, physiographic, hydrologic and hydrogeologic input parameters, from wind sheltering coefficients to aquifer hydraulic conductivity, are required to run the integrated model. One of the most important input parameters is land surface elevation (Figure 4) because it controls the flow paths of surface water. Helicopter measurements of land surface elevation at 400-m spacing were obtained using a global position satellite (GPS) device. The GPS data clearly indicate the Taylor Slough depression extending from the northeast to the southwest. The low elevation "notches" along the Florida Bay coastline are used to represent the coastal creeks, some of which cross the Buttonwood Embankment. Flow resistance parameters at these notches were based on field data and slightly adjusted to better match the measured coastal creek flows.

The leakage coefficient is the most significant parameter for representing the exchange between surface water and groundwater. Spatially variable leakage coefficients were calculated by dividing peat hydraulic conductivity by peat thickness. Peat data used to calculate leakage coefficients were taken from Harvey (2000b). Leakage coefficients for Florida Bay were estimated from a map showing the bay bottom type and estimates of bottom sediment hydraulic conductivity, or aquifer hydraulic conductivity if bottom sediments were absent. In some areas, layers of peat or bay bottom sediments were absent, such as Joe Bay and parts of Florida Bay. In those areas, leakage coefficients were calculated using estimates of the vertical hydraulic conductivity of the Biscayne aquifer.

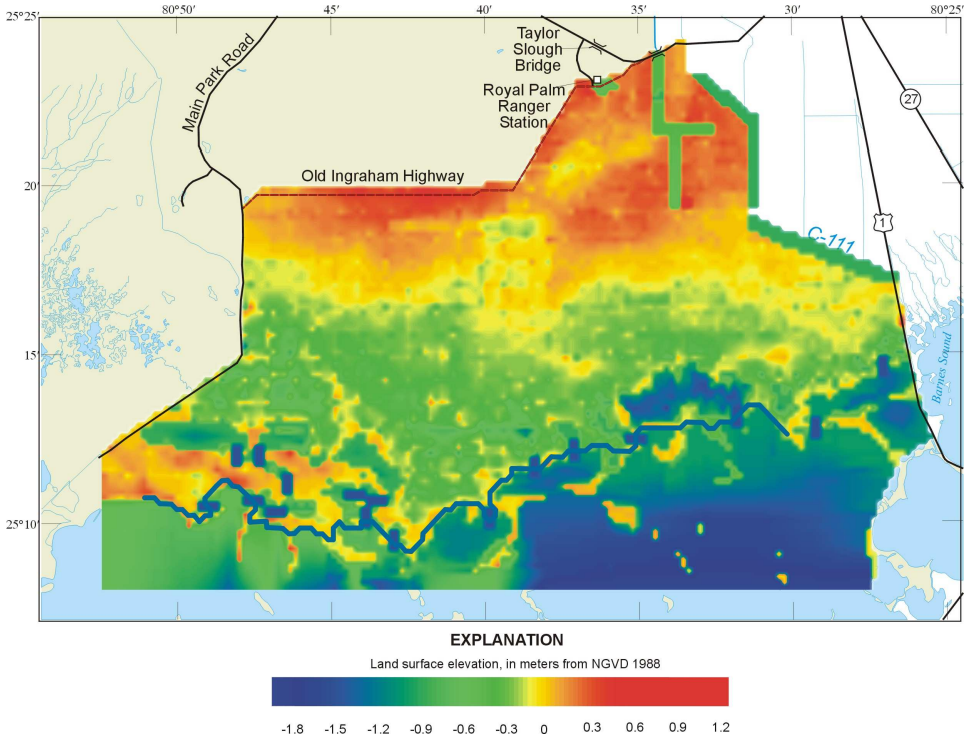

Figure 4. Map showing land surface elevation relative to the National Geodetic Vertical Datum (NGVD) of 1988.

MODEL CALIBRATION AND RESULTS

The integrated surface water and groundwater model was calibrated by adjusting model input parameters until simulated values of stage, salinity, and flow matched with observed values at the wetland and Florida Bay monitoring sites. The integrated model matches measured salinities better than the original SWIFT2D model, although only minor improvements in stage and flow were observed. Simulated exchange rates between surface water and groundwater contain a degree of uncertainty because the model was not calibrated to direct leakage measurements, with the exception of northern Taylor Slough. On the basis of chloride dilution, Harvey et al. (2000a) suggest that groundwater flow into the northern part of Taylor Slough (south of Old Ingraham Highway) may be as much as 3 cm/day. The simulated leakage (0.25 cm/day), however, does not compare favorably with chloride-derived leakage estimates, indicating that further refinements to the model may be required to better represent the exchange between surface water and groundwater in this area. Harvey et al. (2000b) also measured head differences across the peat layer at 11 locations during 6 different field visits. Comparisons of simulated head differences with the observed head differences indicate that directions of vertical leakage are correct, although the actual leakage rates may be in error. Results presented herein should be evaluated with caution because they are based on a model that was not directly calibrated to represent leakage, and thus, the simulated estimates are highly uncertain.

Daily leakage rates between surface water and groundwater are produced as part of the model output for each cell. These daily leakage rates were averaged over the simulation period from

August 1996 to June 1998 to illustrate the spatial variability in surface water/groundwater interaction (Figure 5). These leakage rates do not include recharge or evapotranspiration directly to or from the water table. The model suggests an alternating pattern of downward and upward leakage from north to south (Figure 5). To the north, most leakage is downward into the aquifer. Further south, a large area of upward leakage exists. This area of upward leakage roughly corresponds with the position of the freshwater/saltwater transition zone (shown in Figure 2). In this area, groundwater flowing toward the south moves upward where it meets groundwater with higher salinity. To the south, leakage is downward into the aquifer. The Buttonwood Embankment (Figure 1) impedes surface water flowing south and increases stage levels to slightly higher than stage levels in Florida Bay. South of the Buttonwood Embankment, groundwater discharges upward into the coastal embayments of Florida Bay. This upward leakage could be caused by the higher water levels on the north side of the embankment. The southernmost zone represents downward leakage from Florida Bay into the underlying aquifer. Downward leakage in this zone is probably the result of cyclic flow that often occurs in freshwater/saltwater interfaces within a coastal aquifer (Kohout, 1964; Langevin, 2001). Fresh groundwater flowing toward an interface mixes with saline groundwater. This brackish mixture then discharges into the ocean, coastal estuary, or in this case, into the brackish water wetlands.

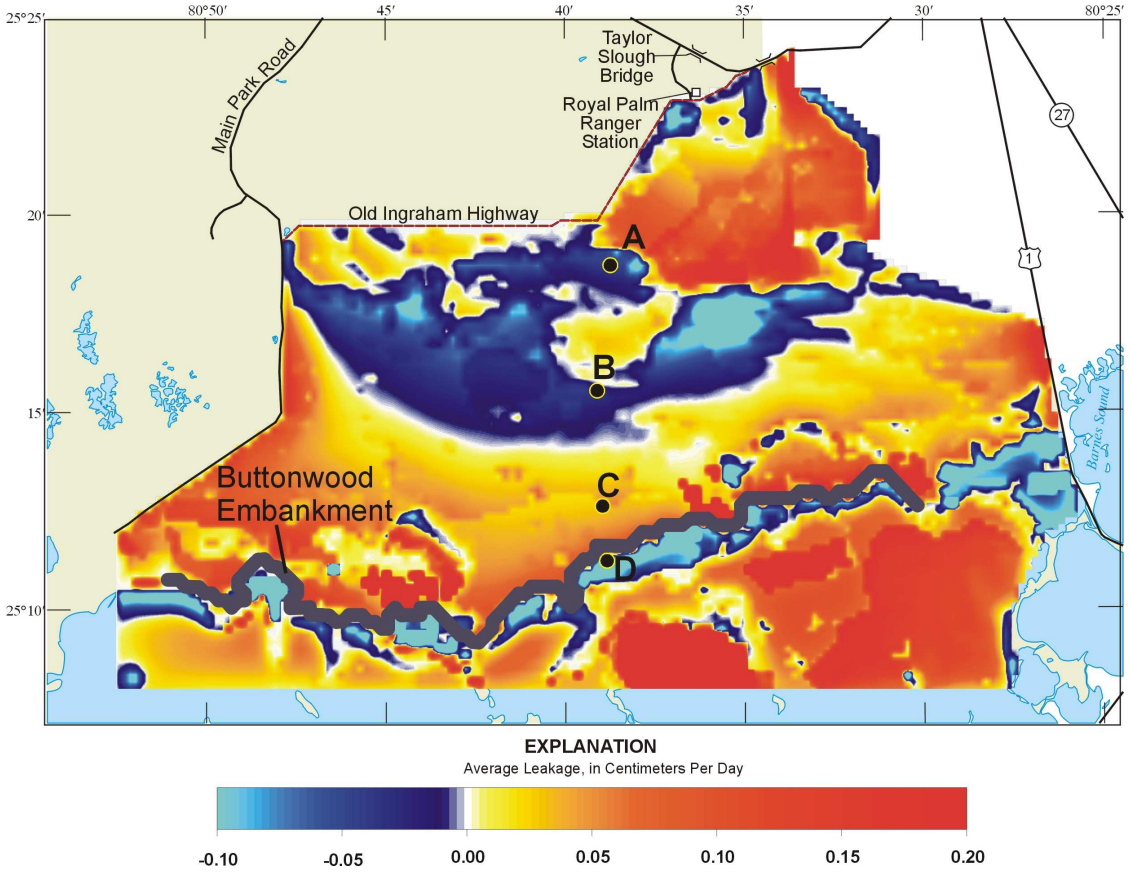

Figure 5. Map showing average leakage rates for the simulation period. Graphs for the four locations are shown in Figures 6, 7, 8, and 9. Positive leakage rates represent downward flow into the aquifer. Negative leakage rates indicate upward flow from the aquifer to the surface water.

The map in Figure 5 shows average leakage rates for the entire simulation period, but daily leakage rates are highly variable and can change direction in response to rainfall events or prolonged dry periods. Leakage maps for specific days reveal similar patterns as the average map, except after significant rainfall events. Graphs of simulated daily leakage, water levels, and salinity were prepared for selected model cells (labeled A through D on Figure 5). The average leakage rate is about –0.05 cm/day at location A, which is in a zone of upward leakage just south of Old Ingraham Highway (Figure 6). Large rainfall events, such as in June 1997, seem to greatly impact the vertical movement of water. Vertical leakage in the area appears to change direction as surface water flows downward into the aquifer. During most of the simulation period, however, leakage is upward into the surface water.

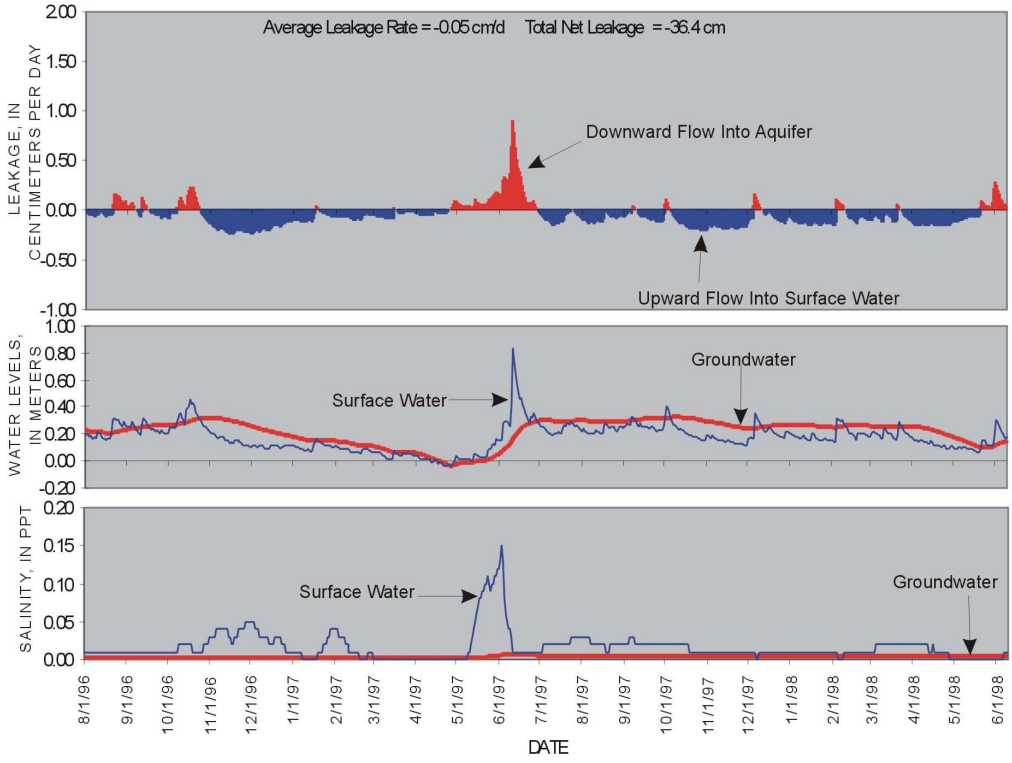

Figure 6. Graphs showing leakage, water levels, and salinity for point A (shown in Figure 5)

Leakage patterns similar to location A also are shown for locations B (Figure 7) and C (Figure 8); after large rainfall events, downward leakage rates into the aquifer are relatively high. During periods with declining surface water levels between rainfall events, groundwater appears to leak gradually upward, mixing with the surface water. Location D, which is located in Florida Bay, appears to respond differently than the other locations, possibly because it is highly affected by stage and salinities of Florida Bay (Figure 9). Based on model simulation, groundwater is leaking upward into the Florida Bay estuary at rates of up to –0.5 cm/day with a salinity of 5 ppt. Unfortunately, there are no field data to support or refute this hypothesis.

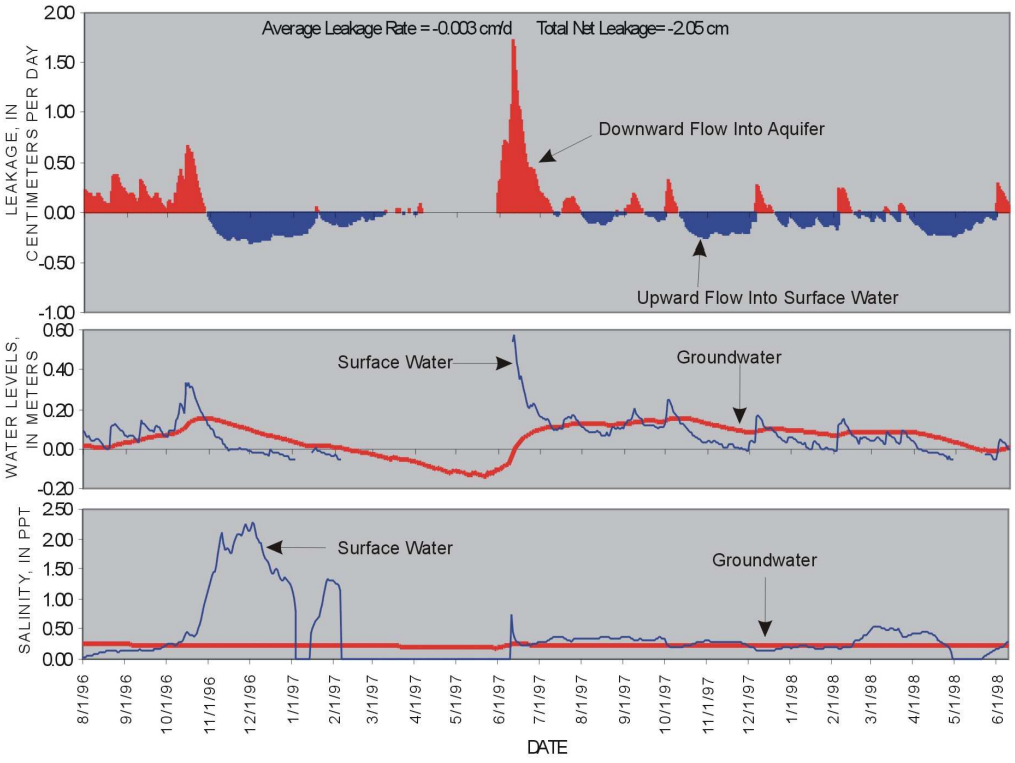

Figure 7. Graphs showing leakage, water levels, and salinity for point B (shown in Figure 5).

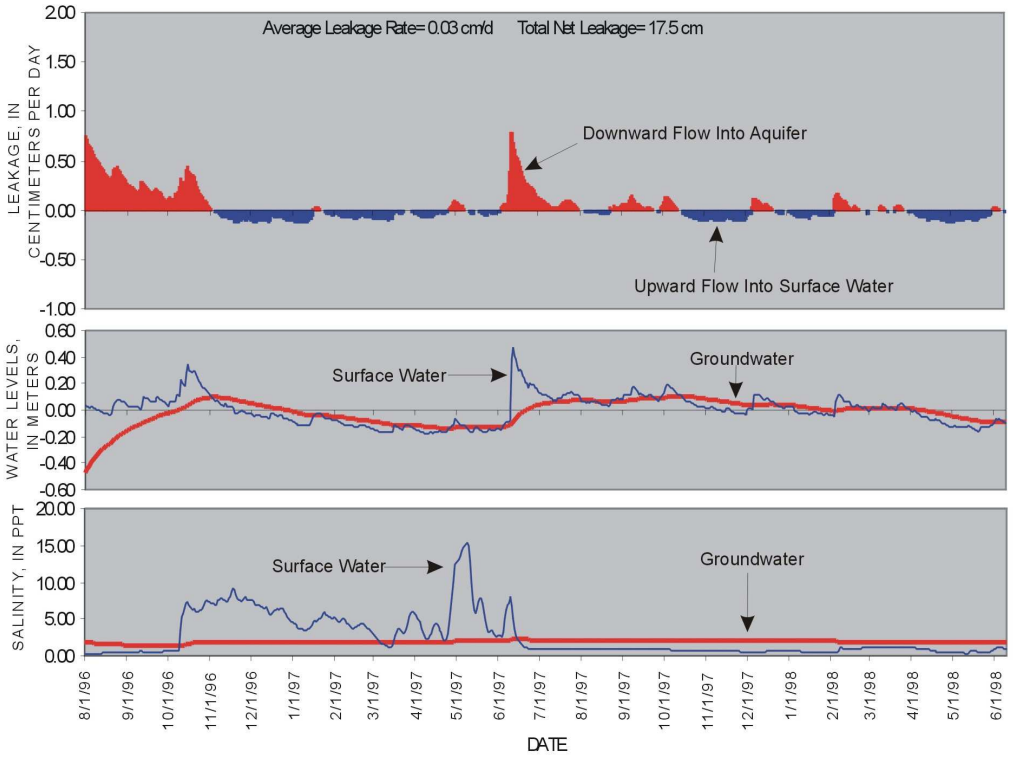

Figure 8. Graphs showing leakage, water levels, and salinity for point C (shown in Figure 5).

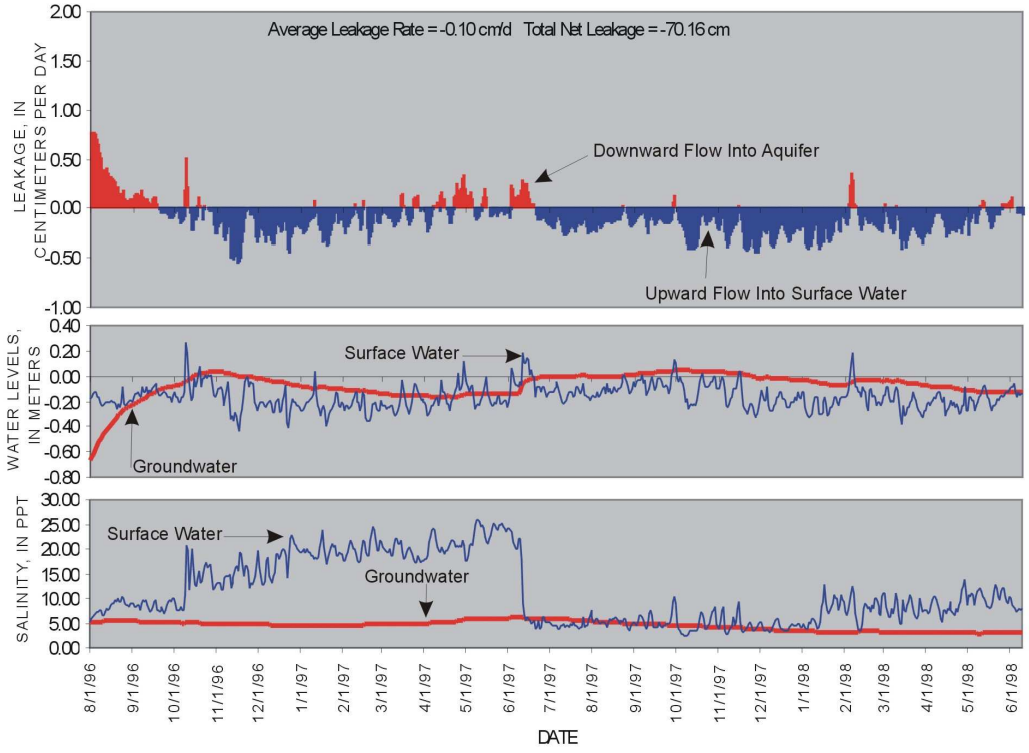

Figure 9. Graphs showing leakage, water levels, and salinity for point D (shown in Figure 5).

The average simulated leakage rate for the entire Taylor Slough area is about 10 cm/yr. This value was calculated for the entire model by subtracting the average of all downward leakage rates (-20 cm/yr) from the average of all upward leakage rates (30 cm/yr). The average annual rainfall rate for southern Florida is about 140 cm/yr. However, evapotranspiration rates in the Everglades may be similar to rainfall rates. Model results suggest that surface water and groundwater interactions are an important component of the water budget for the Taylor Slough area. However, rainfall and evapotranspiration are probably the dominant components of the hydrologic system.

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